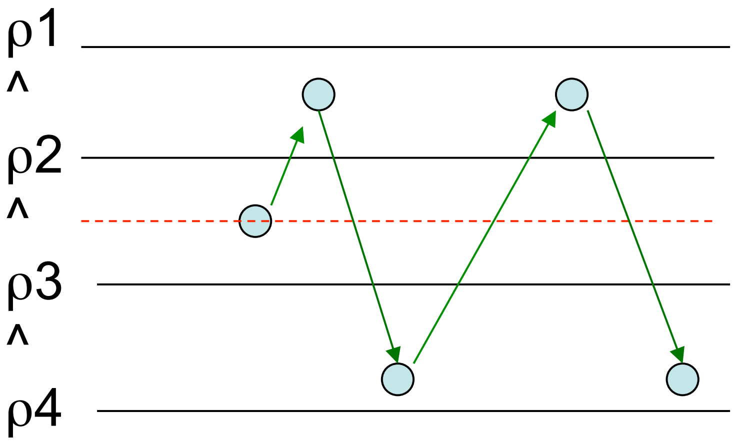
MAR650 Lecture 10: Coastal Internal Waves and Their Impacts on Plankton Dynamics



The buoyancy force defined as its "weight" equals to:

$$F_g = -g(\rho_b - \rho_s)$$

The frequency of the blob's oscillation is related to how fast it changes direction, It is controlled by the buoyancy force. In fact, the frequency of the oscillation is equal to

$$\boxed{N = \sqrt{-\frac{g}{\rho_o}\frac{\partial \rho}{\partial z}}}$$

→ Brunt-Väisälä frequency

Internal wave frequency:

$$\boxed{f \le \omega \le N}$$

Note: Major materials from my graduate student Lai's Ph.D. thesis work

Hydrostatic

$$\frac{\text{Surface elevation}}{\text{Local water depth}} = \frac{\zeta}{H} \ll 1$$

Large-scale motion in which the vertical motion is at least one order of magnitude smaller than the horizontal motion.

Vertical convection, over-turning, and high frequency internal waves are not resolved.

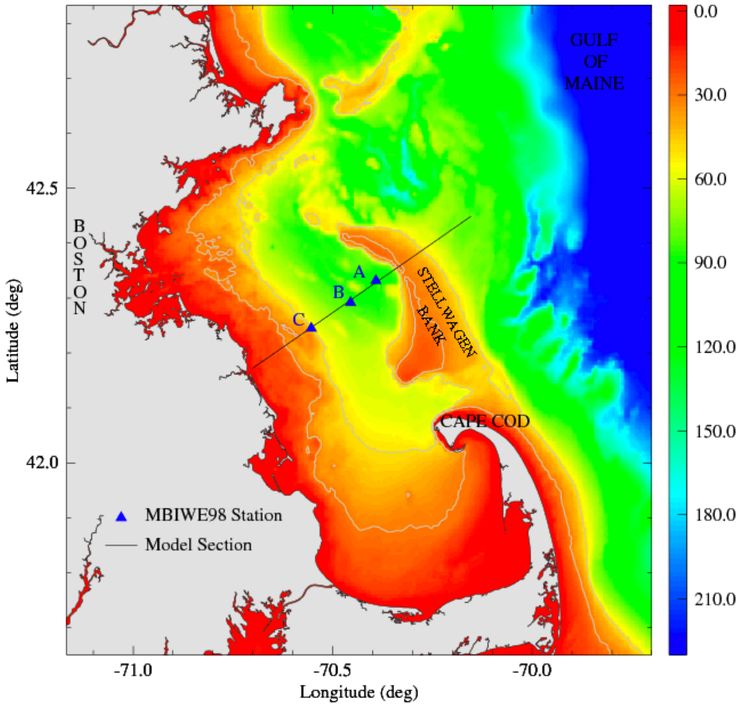
Non-hydrostatic

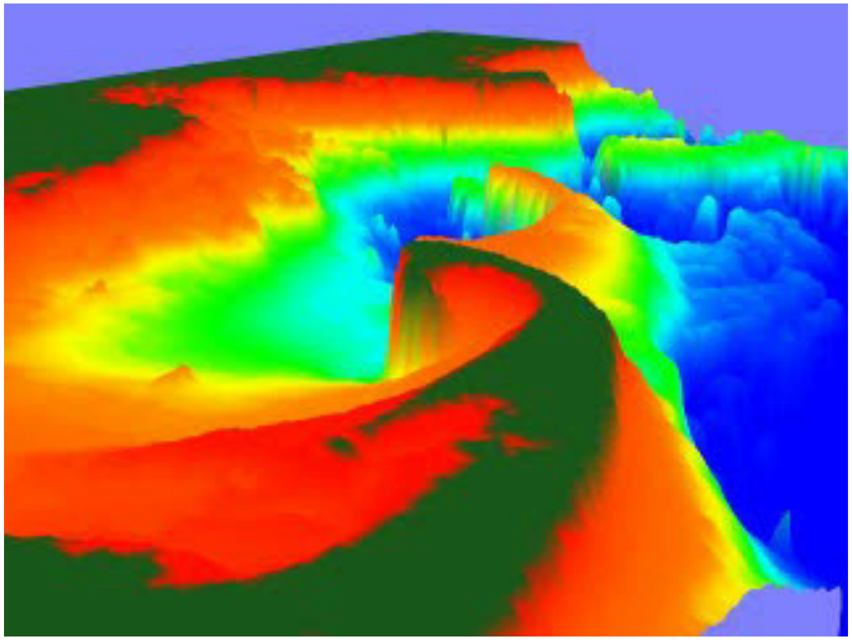
$$\frac{\text{Surface elevation}}{\text{Local water depth}} = \frac{\zeta}{H} \sim 1$$

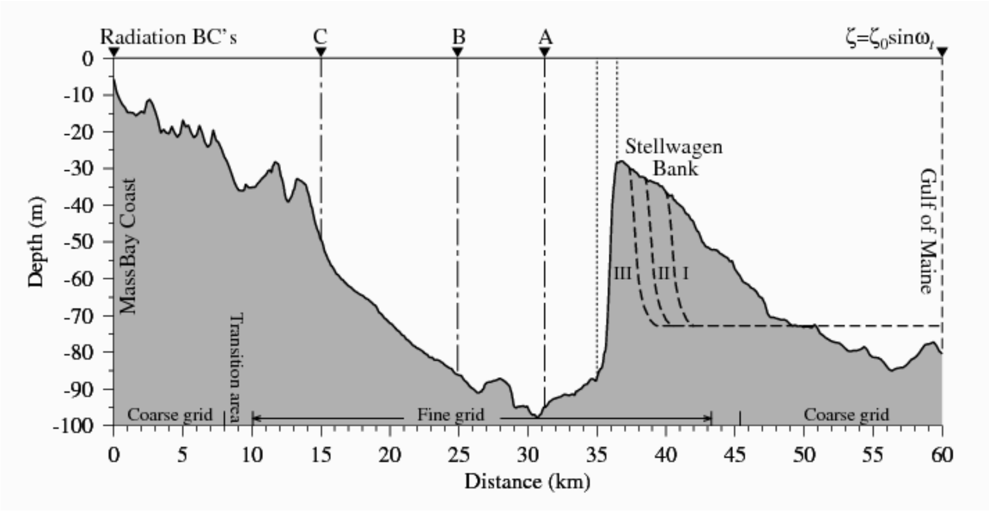
Small-scale motion in which vertical motion is the same order of the horizontal motion.

Vertical convection, over-turning, and high frequency internal waves can be resolved.

Stellwagen Bank, Massachusetts





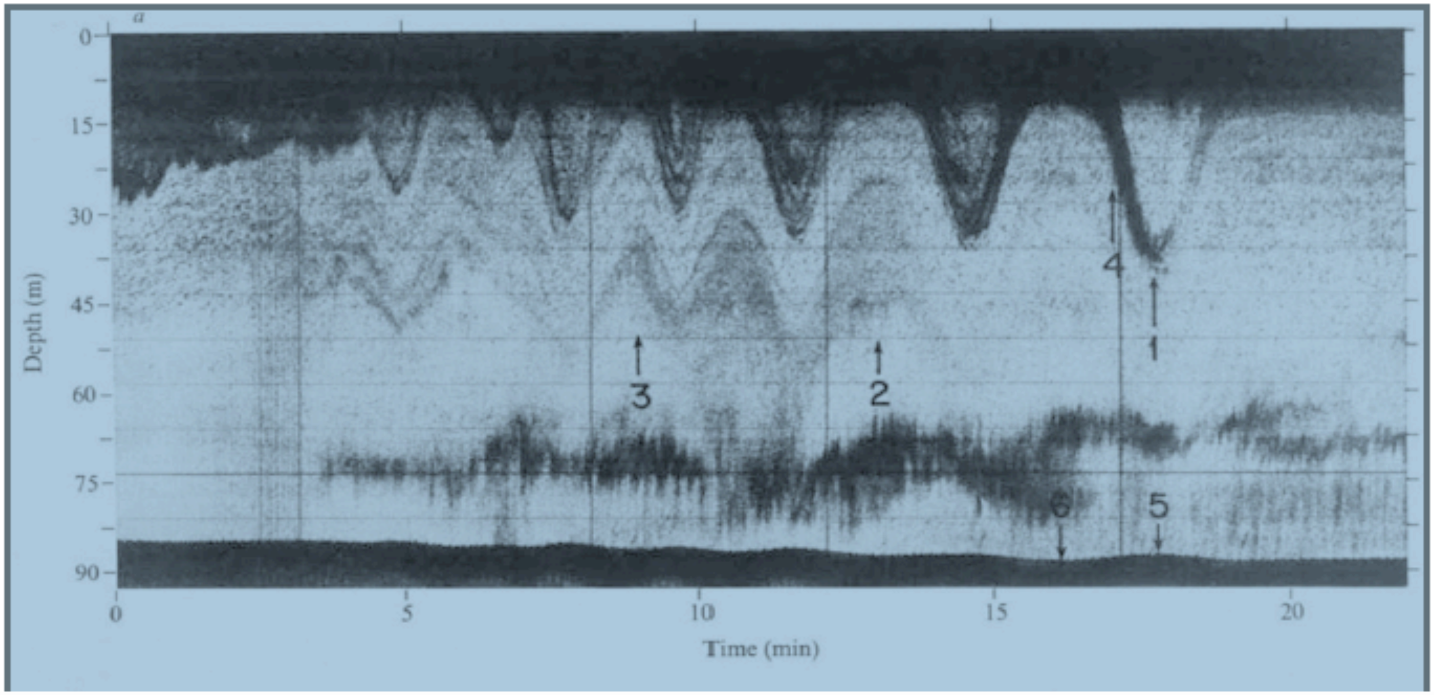


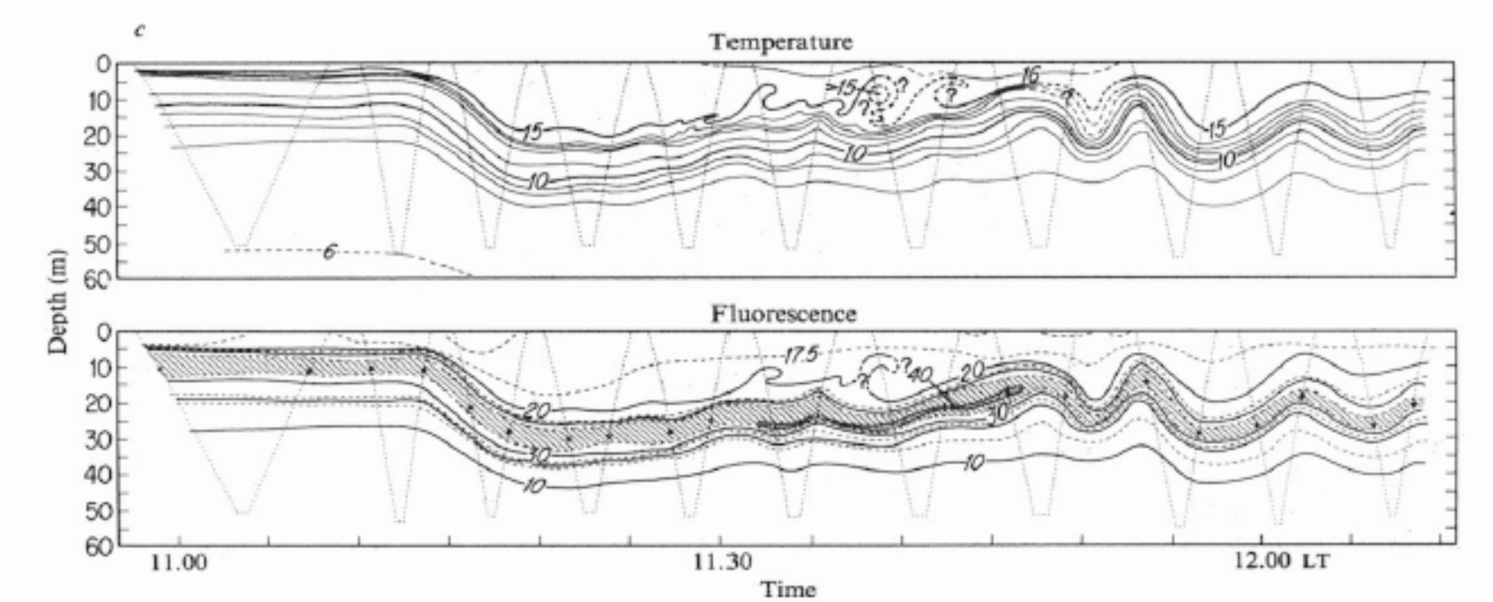
High-frequency internal waves:

Period: ~10 minutes
Wavelength: 200 m
Vertical displacement: 30-40 m
Phase speed: 40-60 cm/s
Solitary wave numbers: 7-12

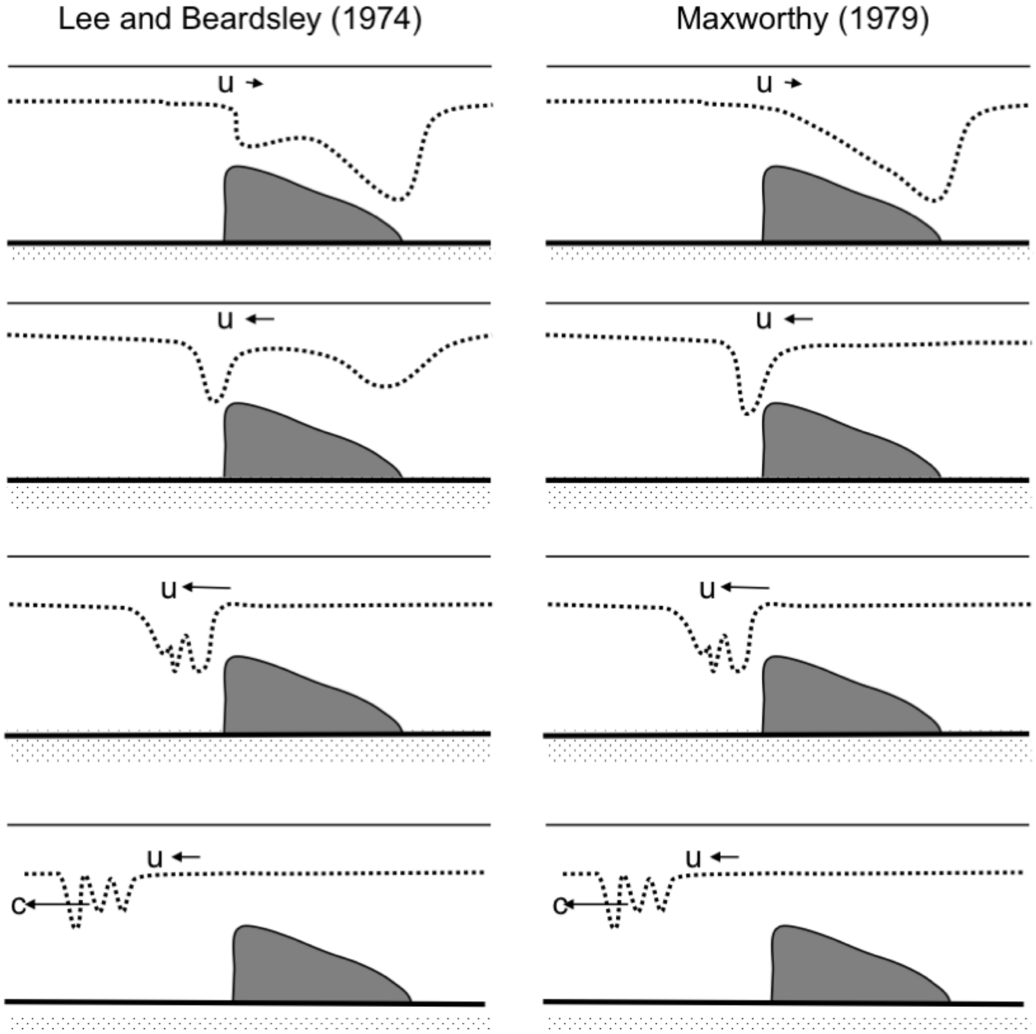
Note: the animation is from Rich Signell at USGS

Huary et al. (1979), Nature, 278, 22.

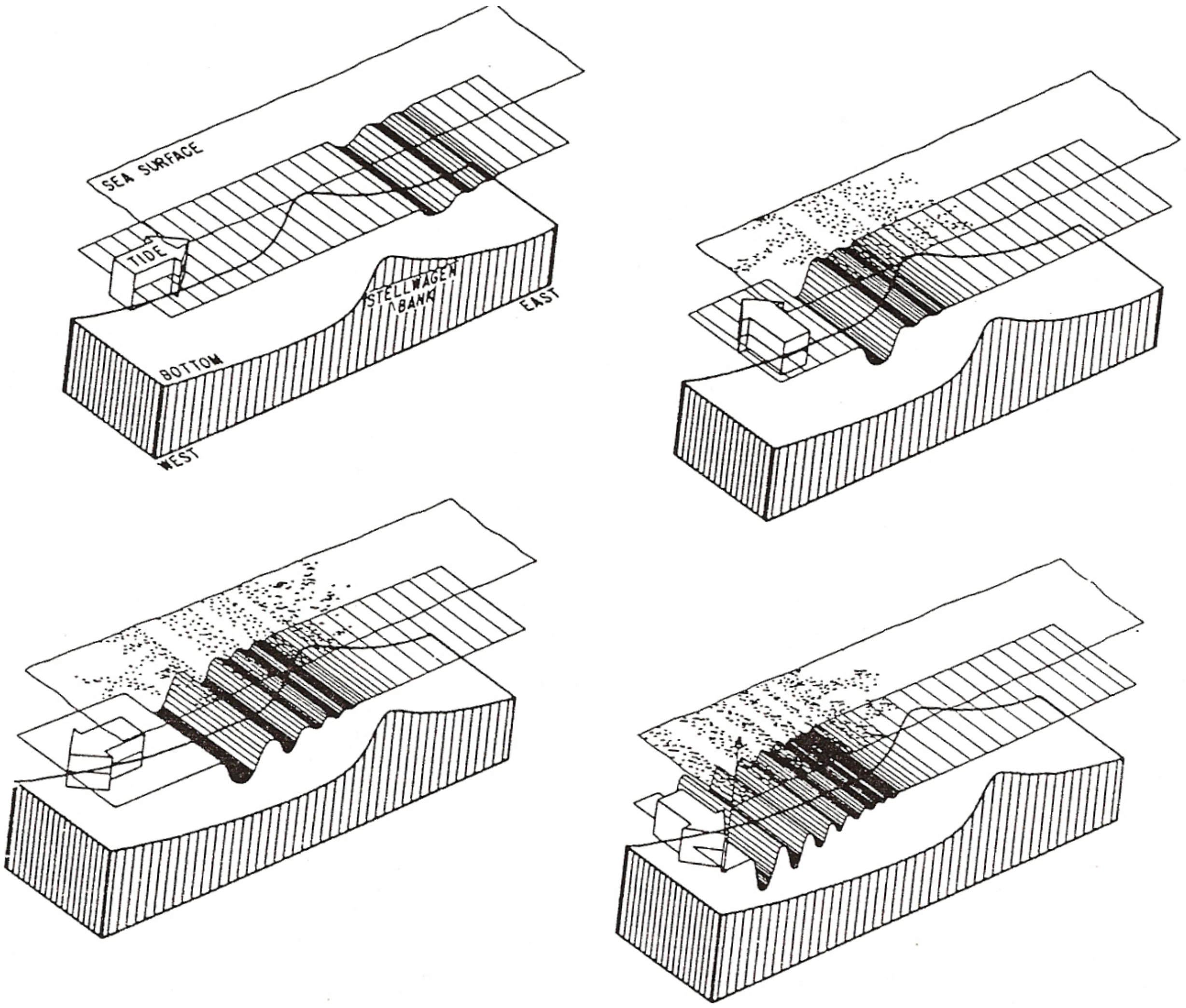




Theory of internal wave generation over Stellwagen Bank



Huary et al. (1979), Nature, 278, 22.



The plankton dynamics derived from an traditional internal wave theory

Questions:

- Is our understanding of high-frequency internal wave dynamics based on relaxation of density depression on the lee side correct?

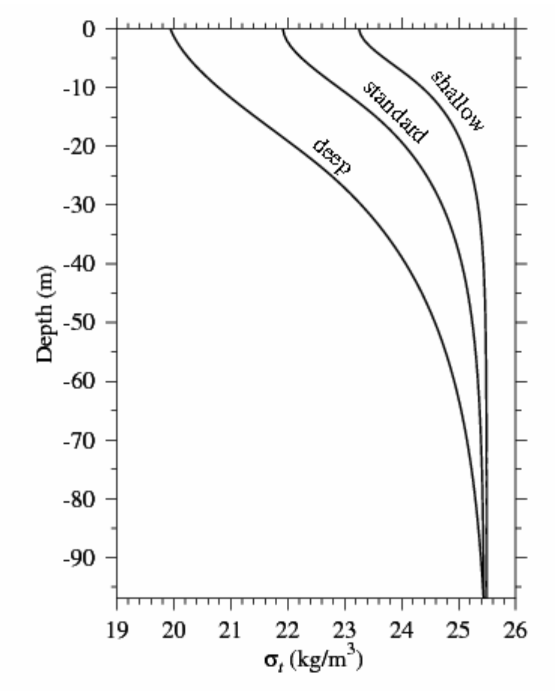
- How does the high-frequency internal waves propagate and dissipate from their generation region to the coast?

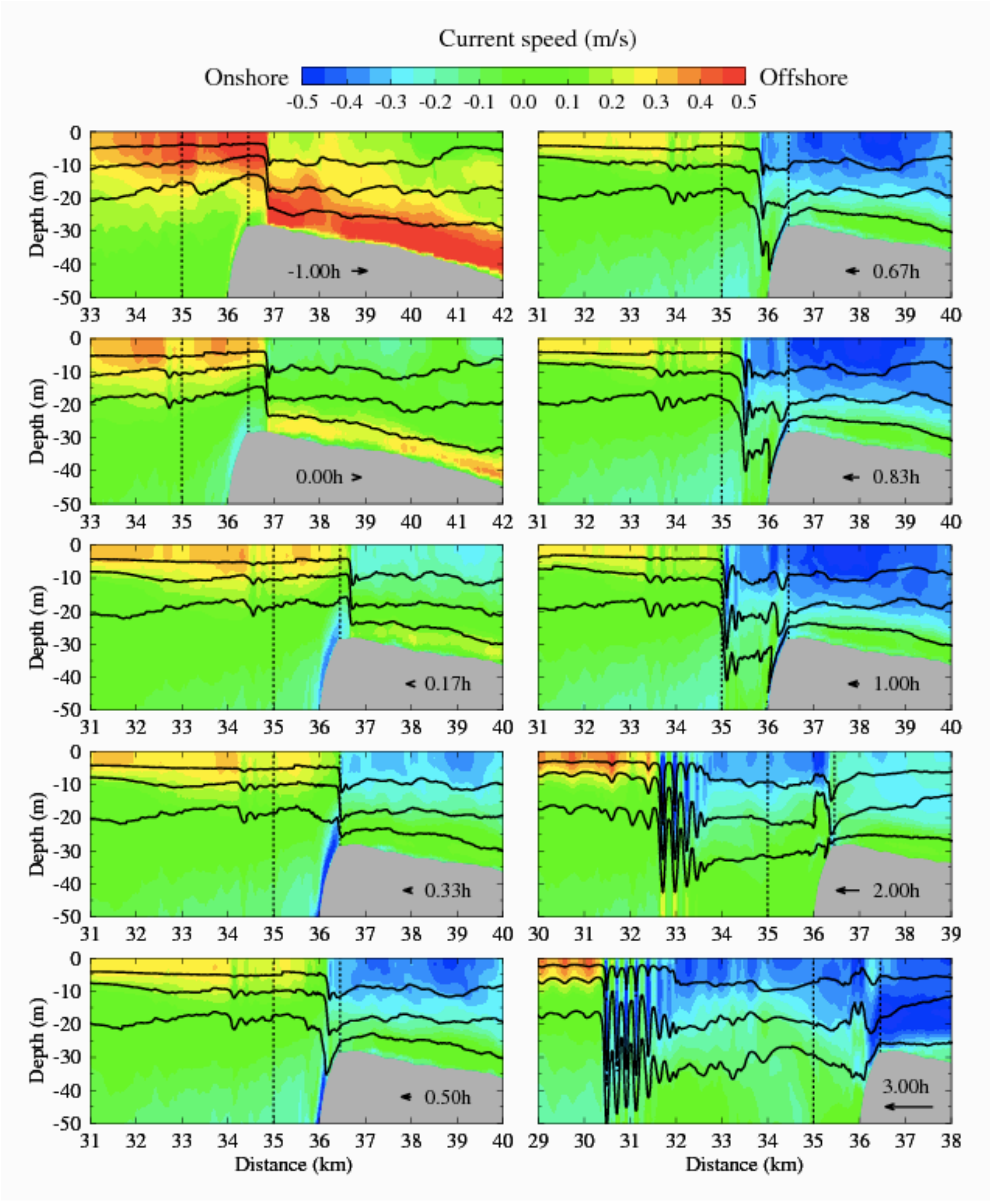
- Is the earth's rotation important for high-frequency internal wave generation and propagation?

- How does the high-frequency internal waves influence the spatial and temporal variation of plankton over steep bottom topographic bank?

Experiment 1:

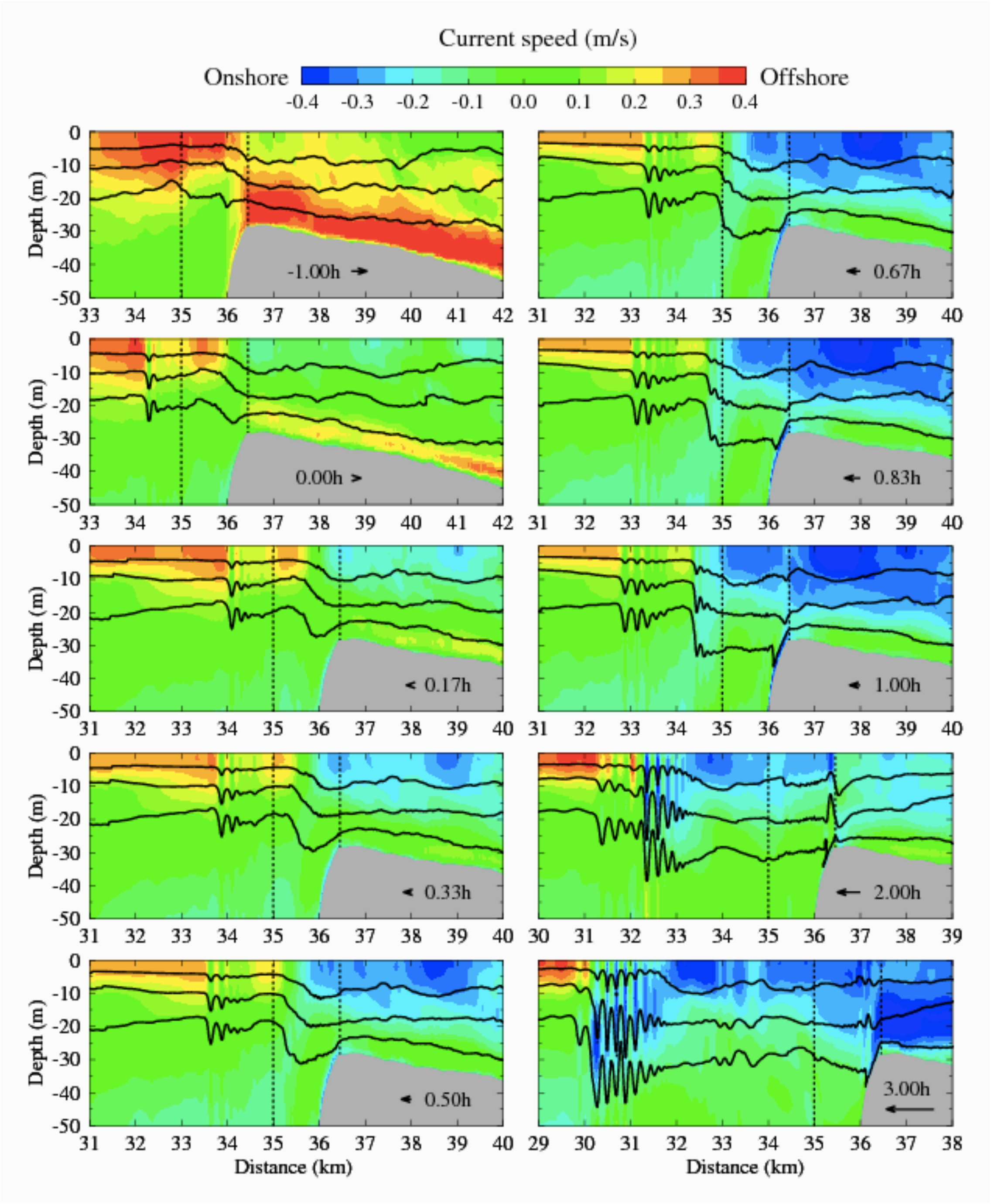
Spring tidal forcing
Standard stratification
No earth's rotation
Constant viscosity of 10^{-6} m^2/s





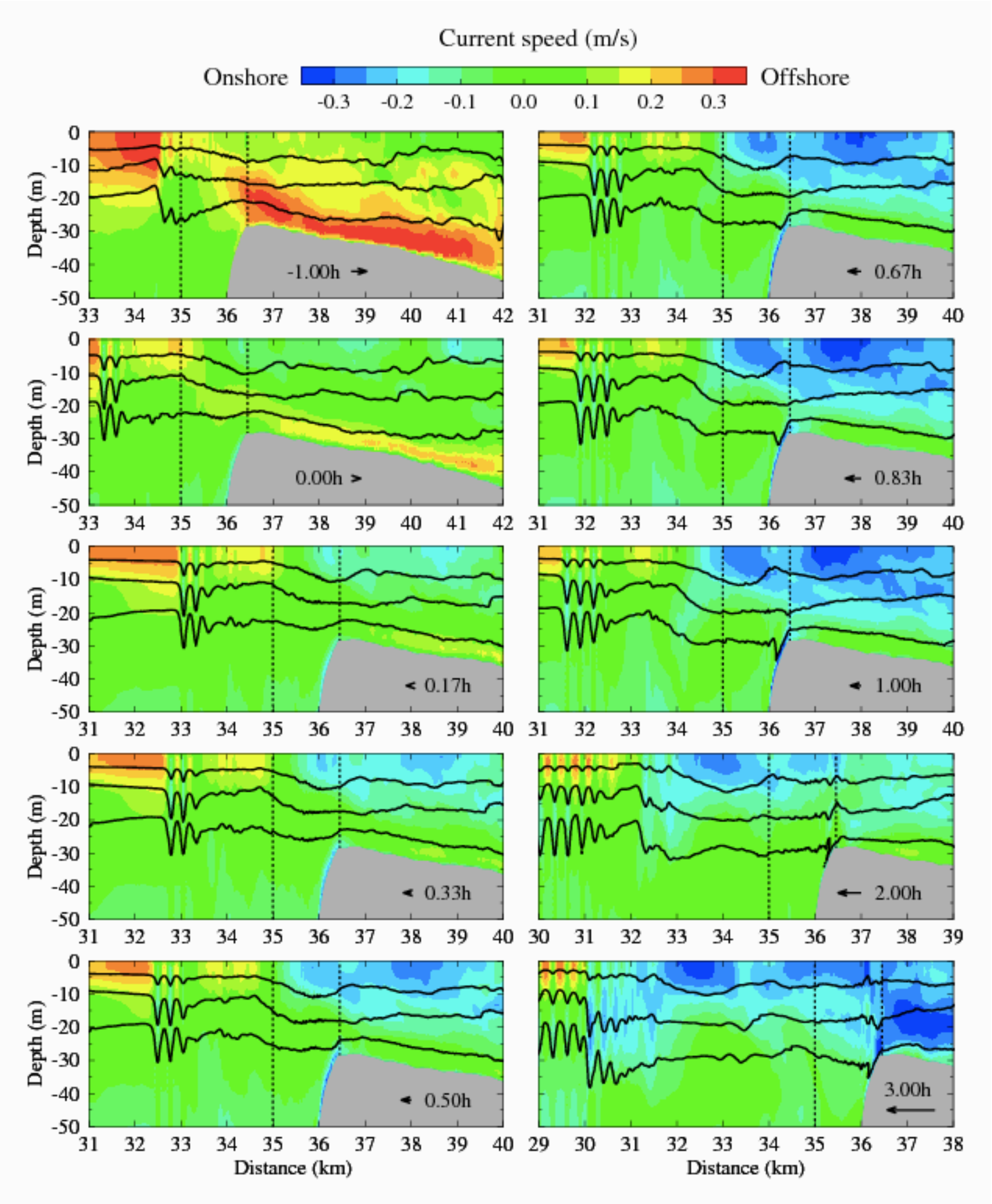
Experiment 2:

Mean tidal forcing
Standard stratification
No earth’s rotation
Constant viscosity of
10^{-6} m^2/s



Experiment 3:

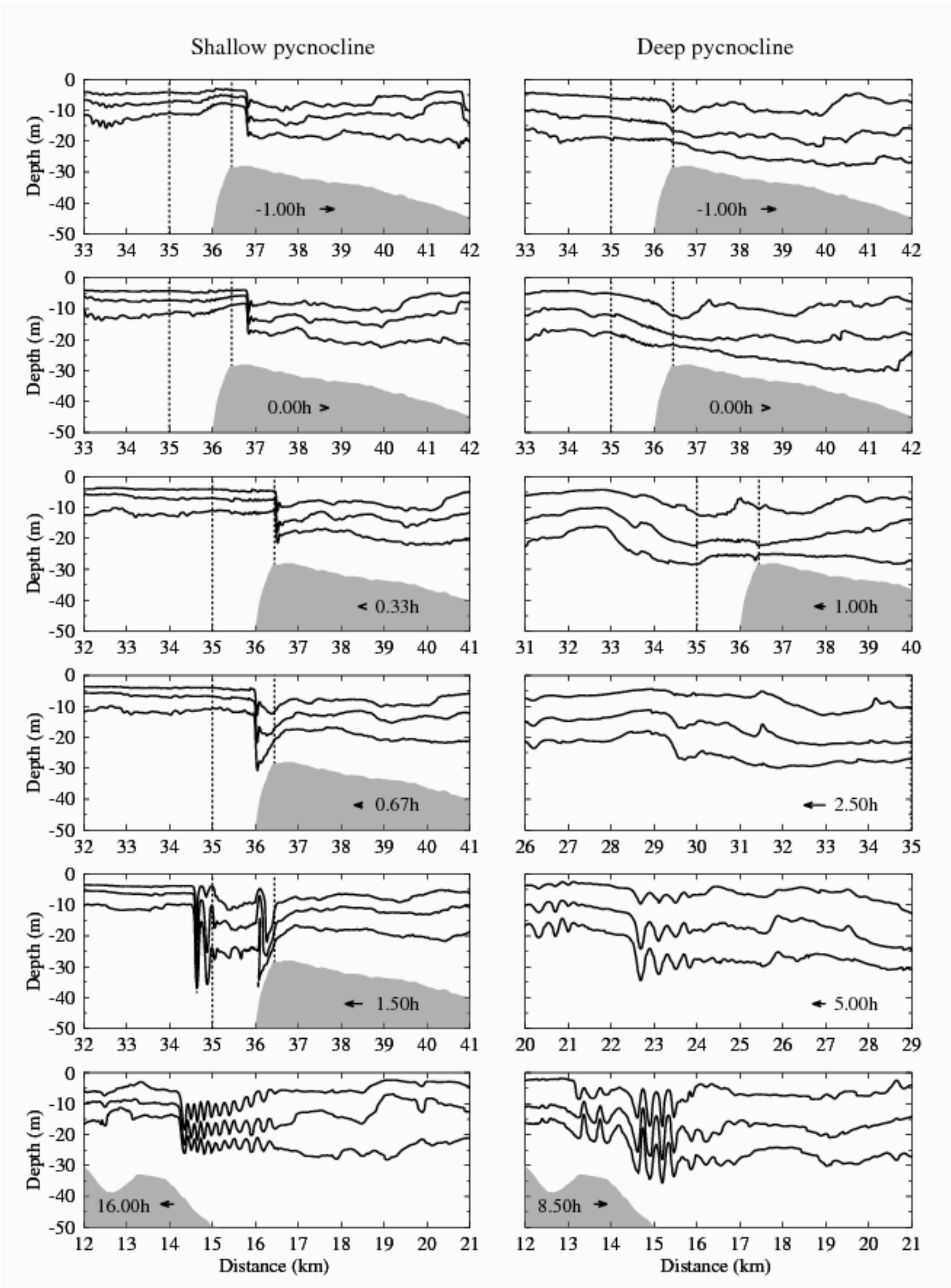
Neap tidal forcing
Standard stratification
No earth's rotation
Constant viscosity of
10^{-6} m^2/s



Experiment 4:

Mean tidal forcing
Shallow pycnocline
Deep pycnocline

No earth's rotation
Constant viscosity of 10^{-6} m^2/s



Conclusion 1:

- High-frequency internal waves observed over Stellwagan Bank is generated through three phases:

  a) forming an initial warm front as a result of partial blocking of the stratified tidal flow on the bay-side frank of the bank;

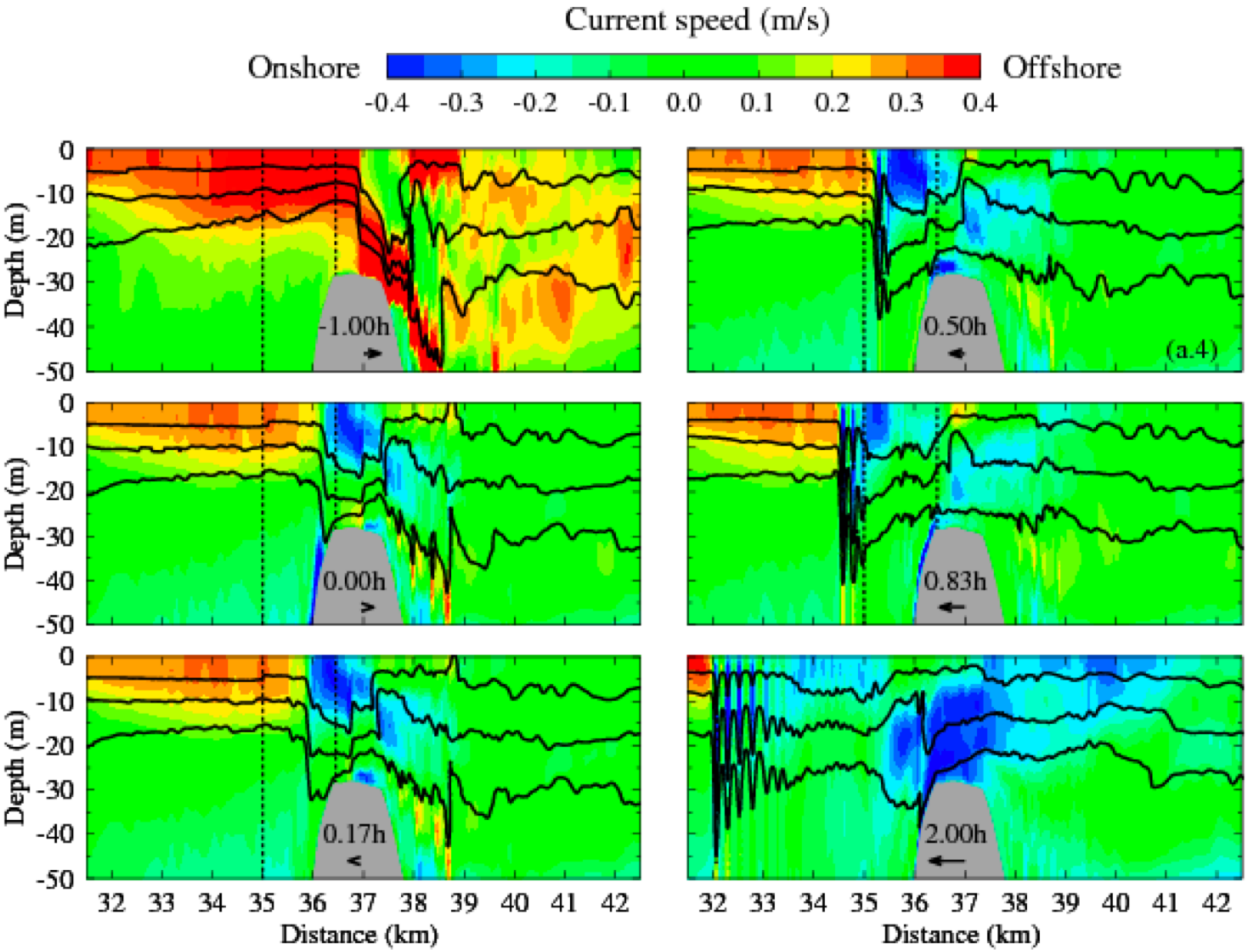
  b) steeping of the thermal front due to increase of nonlinear interaction of tidal currents with steep bottom topography;

  c) evoluting into a wave train owing to effects of dispersion and nonlinearity

These processes do not change for different background stratification and tidal forcings

Lee and Beardsley (1974): correct, but Maxworthy (1979) does not apply.

Why isn't Maxworthy's (1979) theory applied? Missing front!



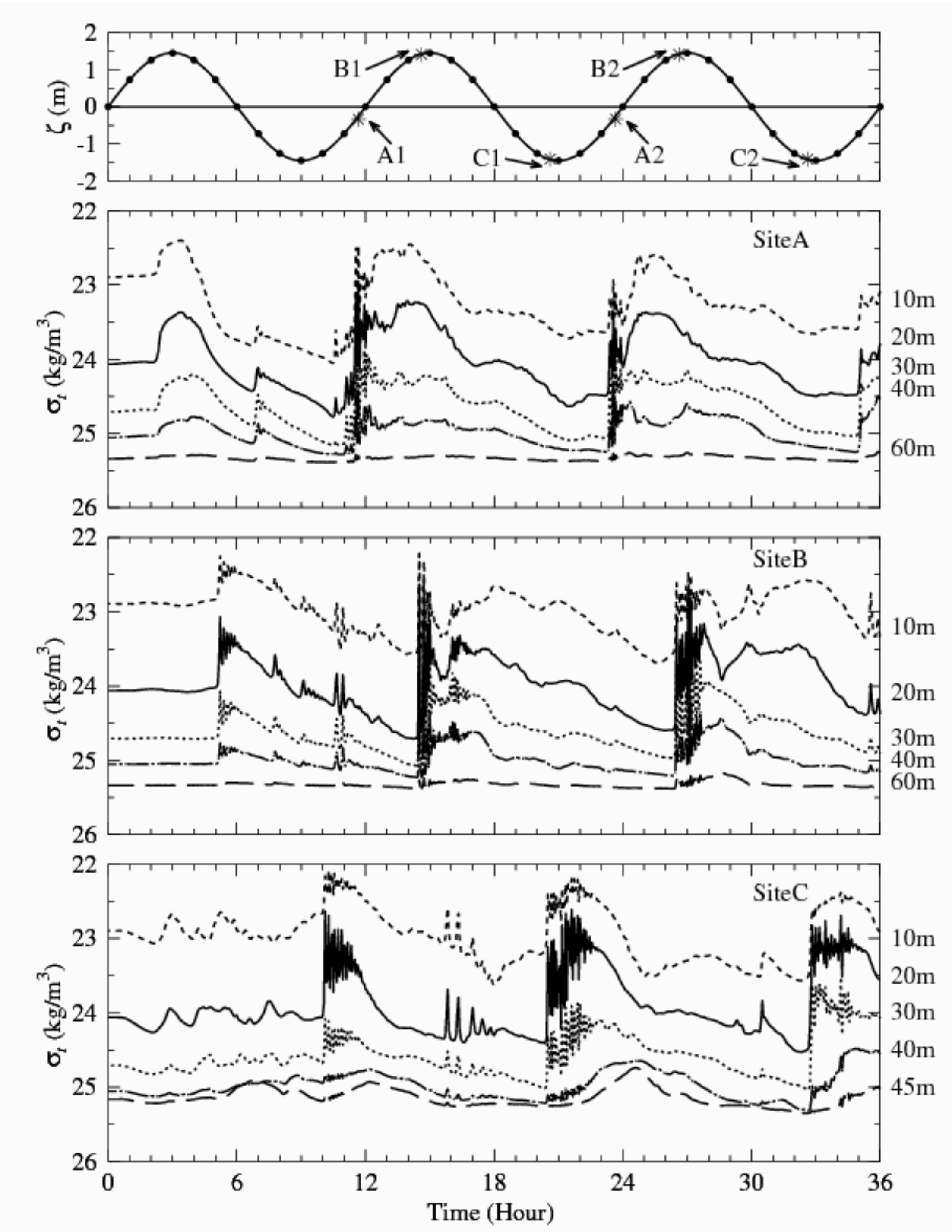
High-frequency internal waves are generated in the early flood tidal period after ebb-flood transition and propagate westward as a finite-amplitude solitary package.

Phase speed is 0.4-0.6 m/s

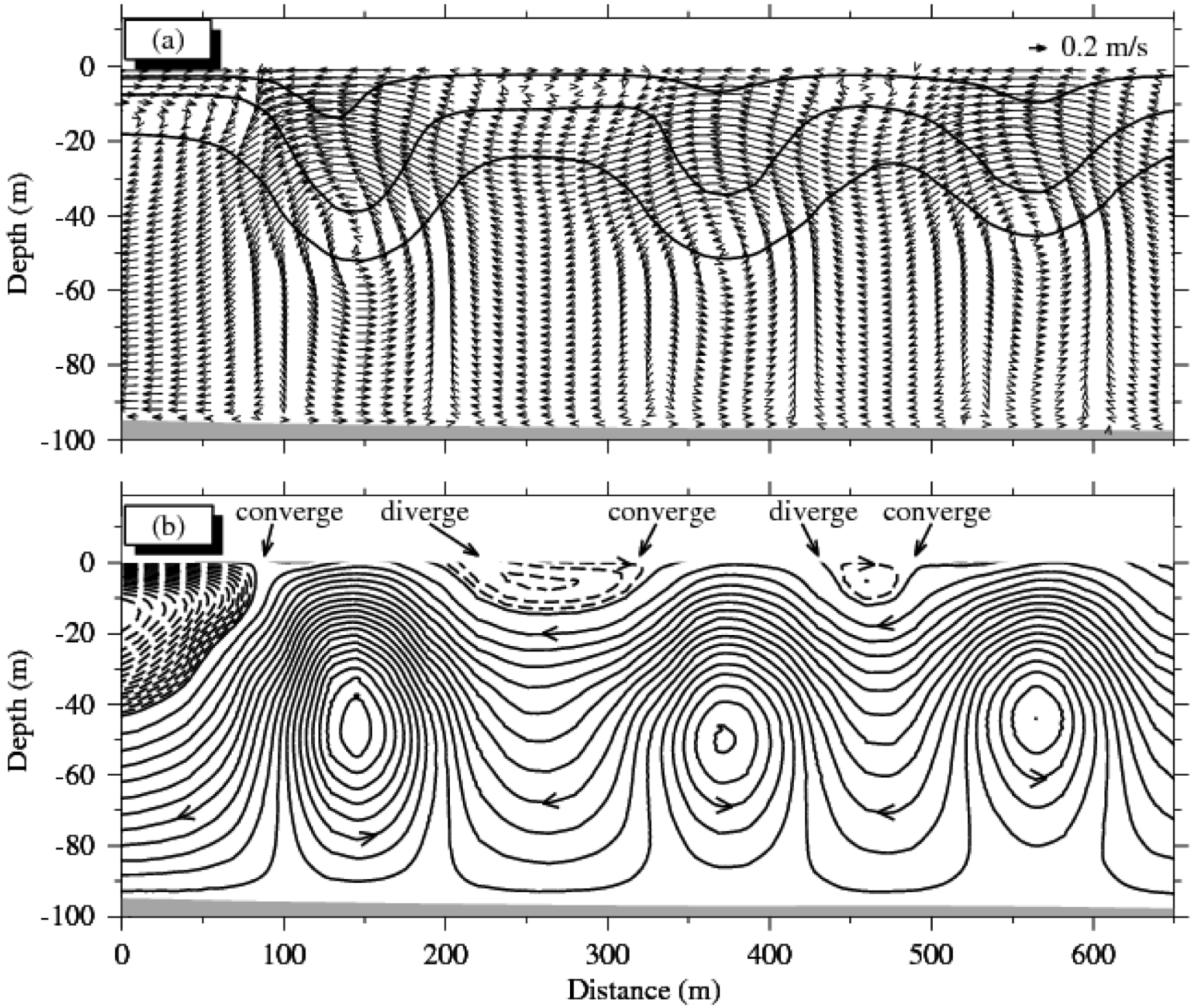
Wavelength: 200 m

Vertical displacement:

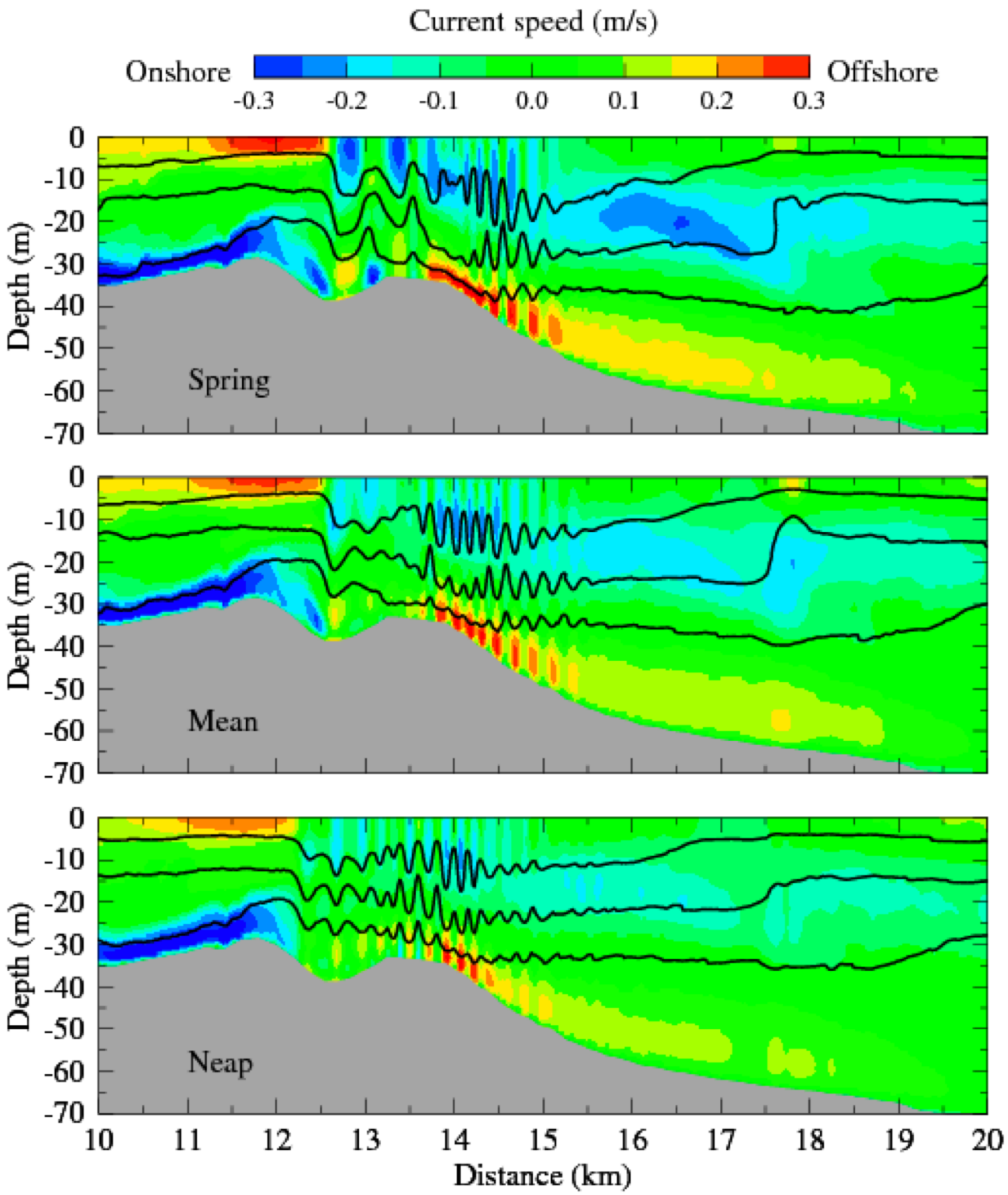
20-30 m



Velocity within the internal solitary waves



Internal wave shoaling and dissipation



Is the earth’s rotation important?

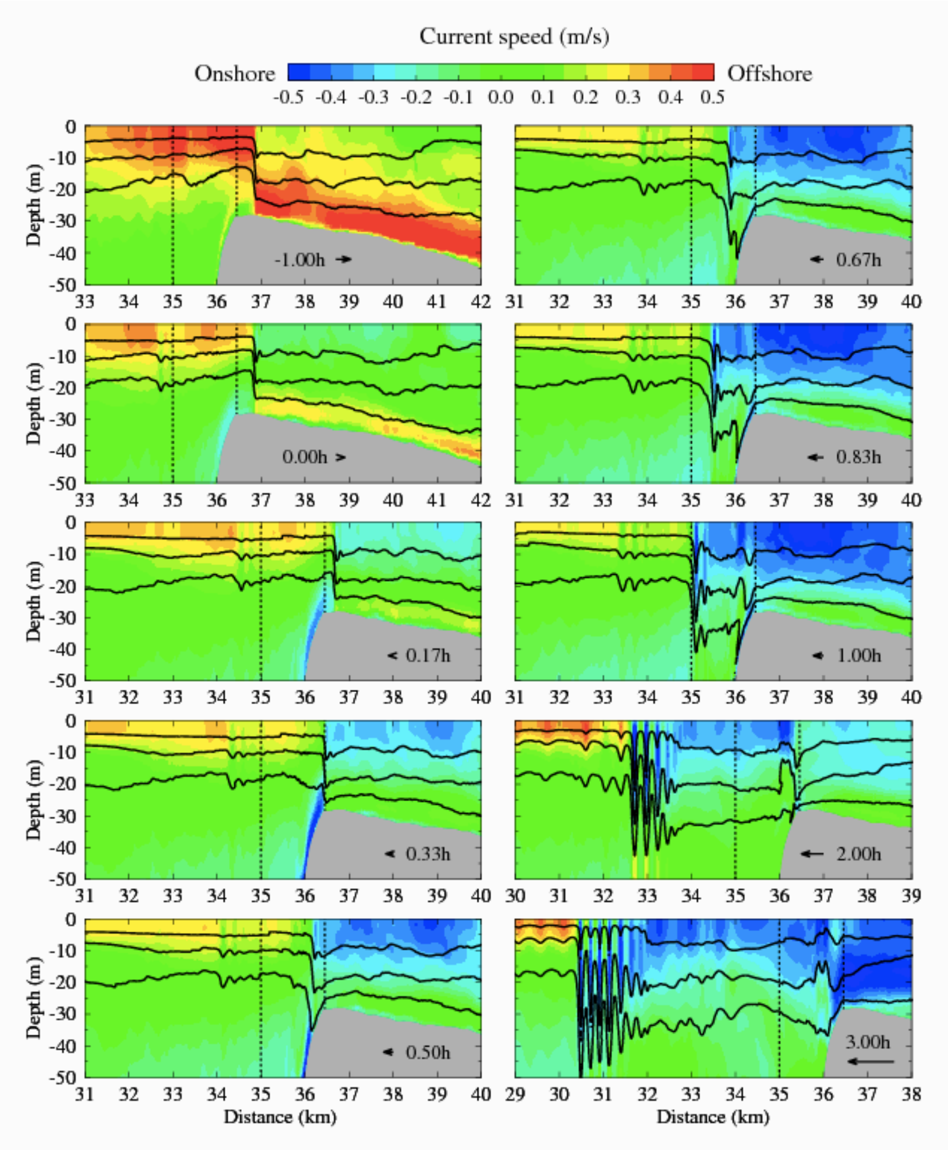
Scaling analysis:

$$\frac{\sigma}{f} \sim \frac{T_f}{T_{ISW}} \sim \frac{15-17 \text{ hours}}{10 \text{ minutes}} >> 1$$

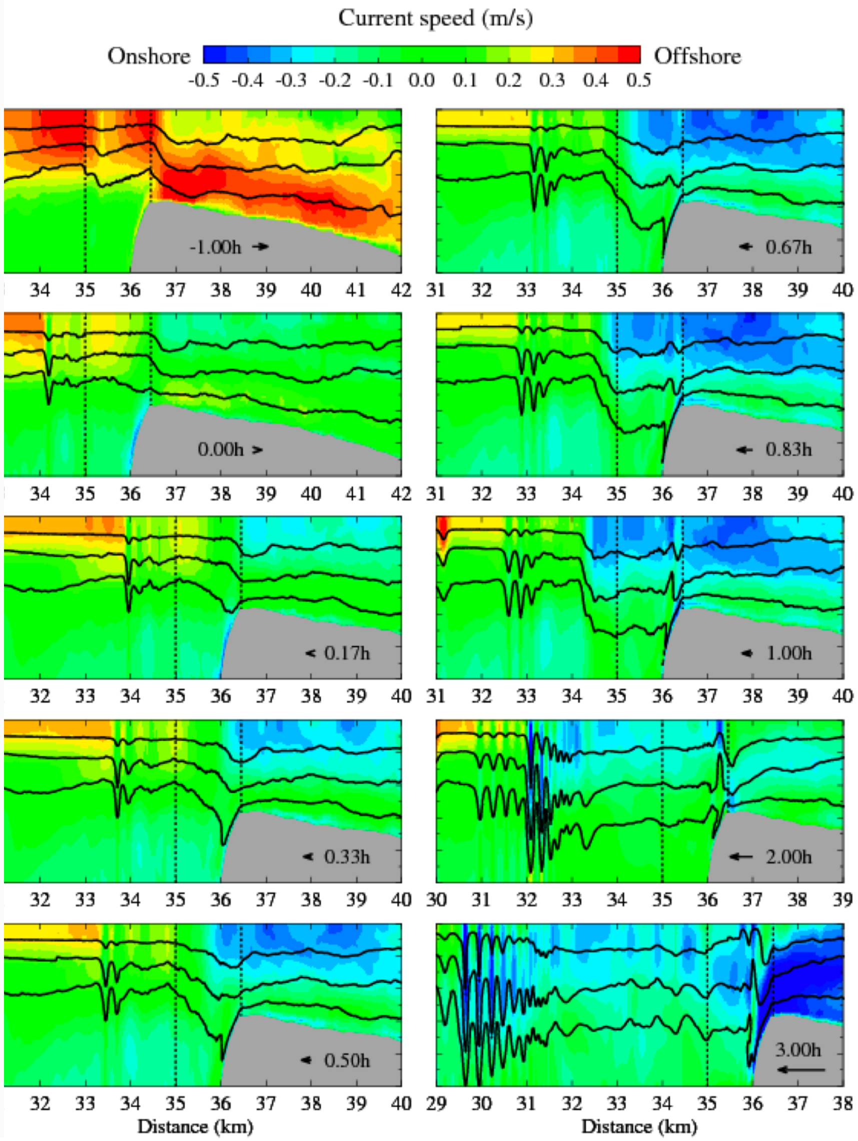
The Coriolis force is generally not taken into account in the study of the high-frequency internal solitary waves.

Is it correct?

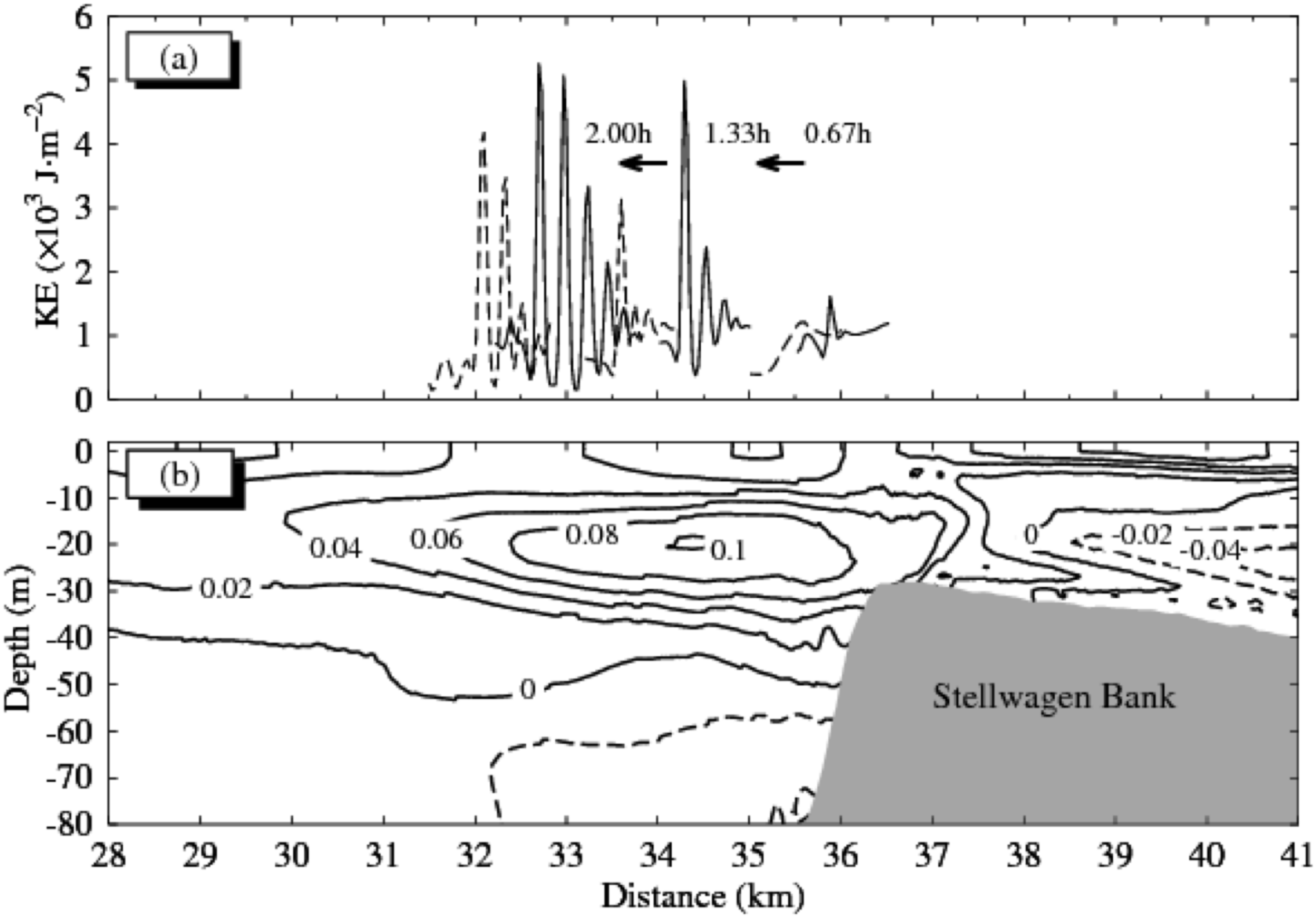
Without the earth’s rotation



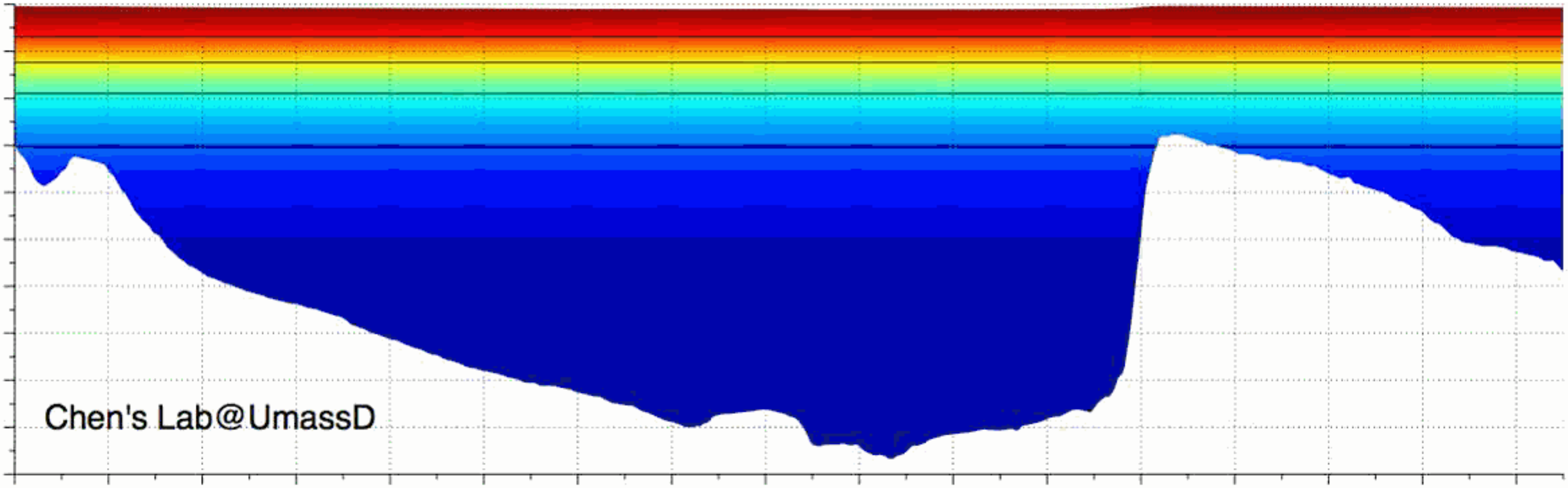
With the earth’s rotation



The Coriolis force converts the cross-bank tidal kinematic energy to to the along-bank direction: contribute to tidal rectification



Chen and Beardsley (1995) and Chen et al. (1995)


Chen's Lab@UmassD

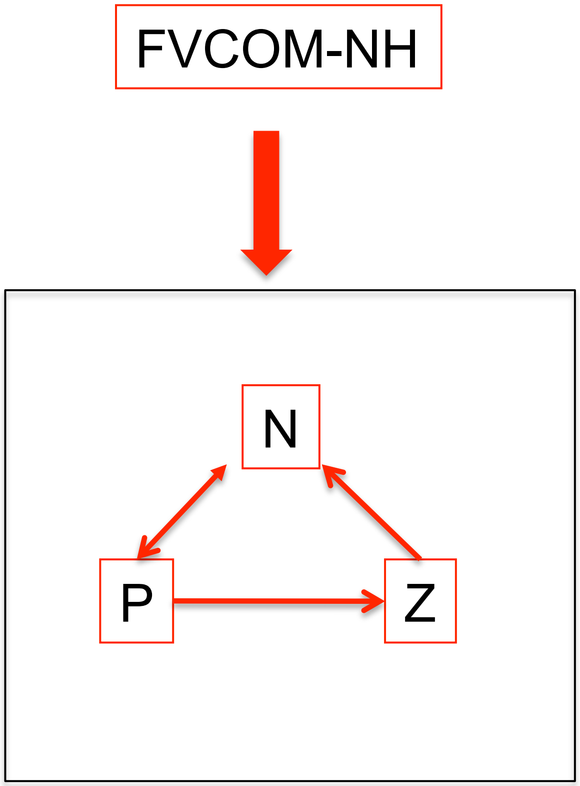
The high-frequency internal solitary waves are the leading edge feature of internal tidal waves, so that their phase speed is controlled by the internal tide and given as

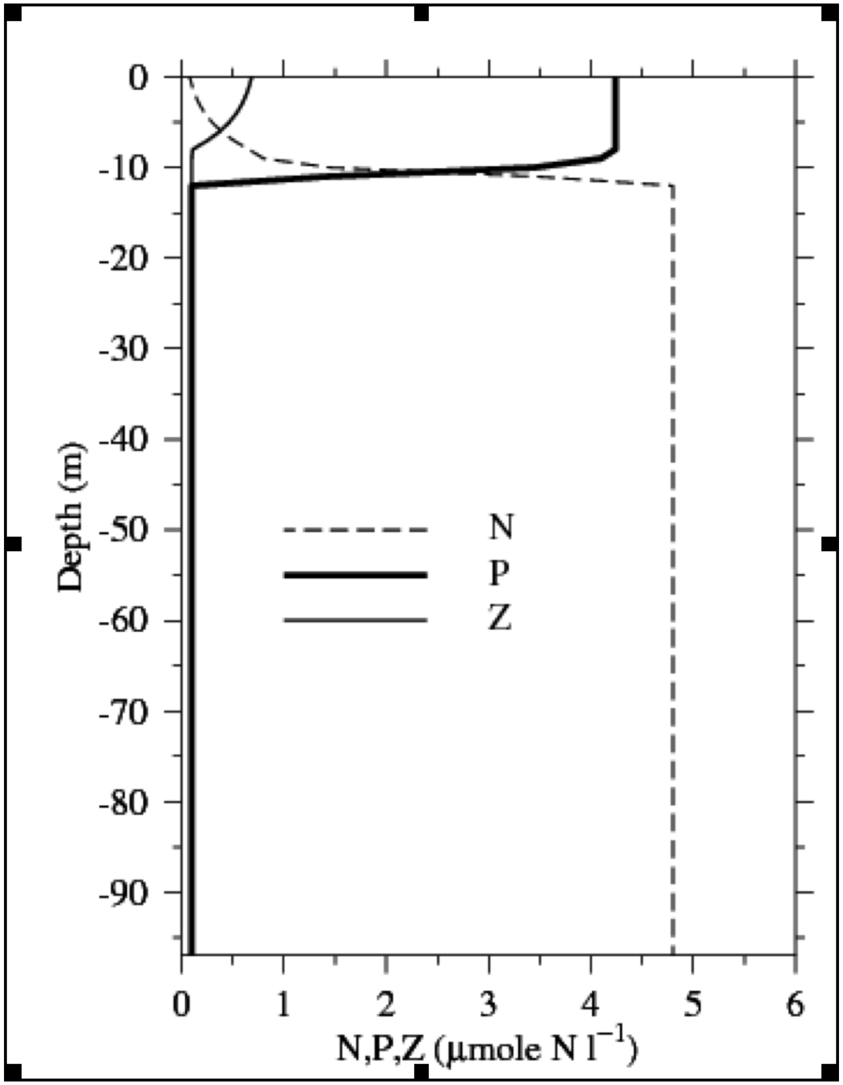
$$c_f^2 = \frac{c_o^2}{1 - f^2/\omega^2}$$

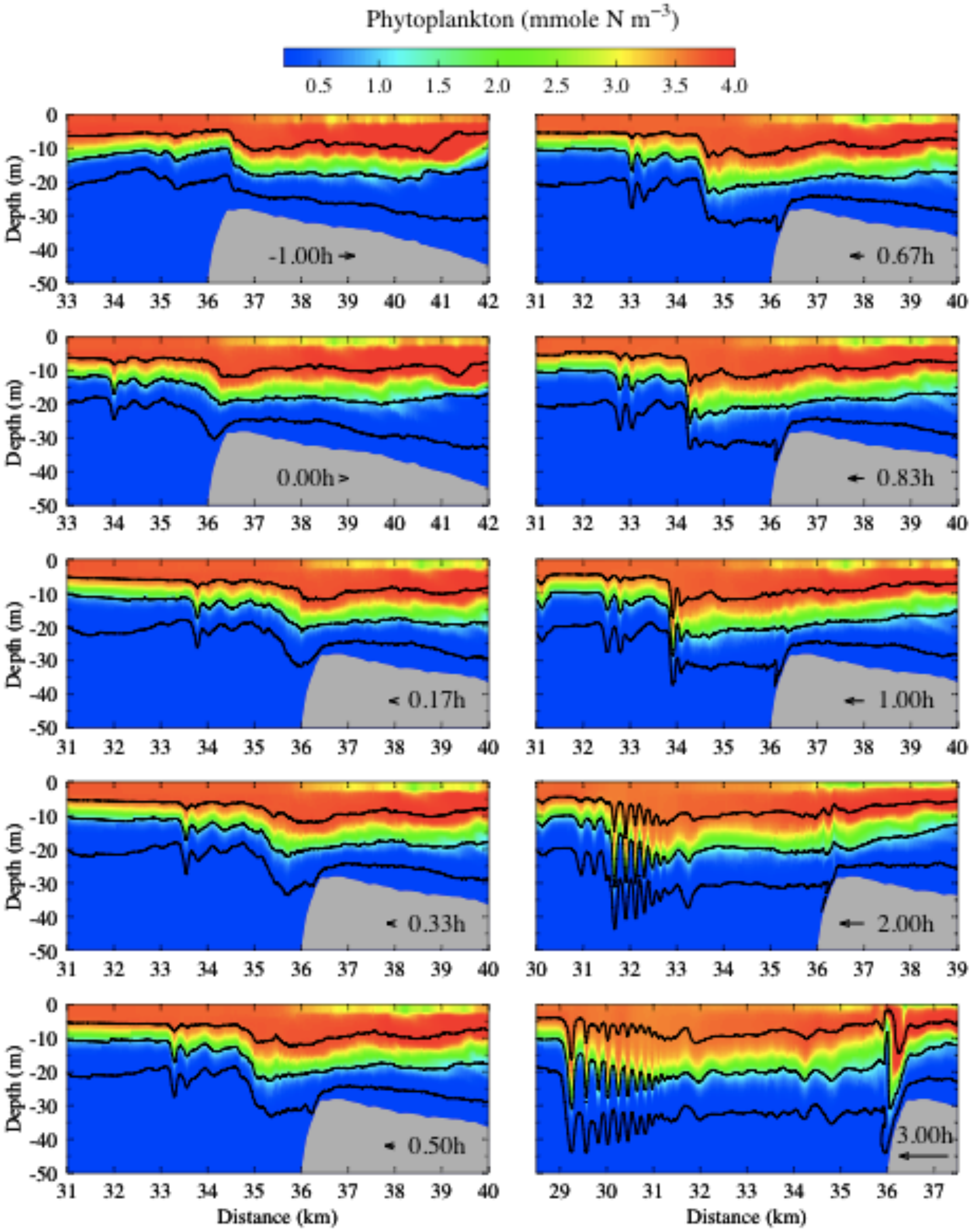
Gerkema (1996)

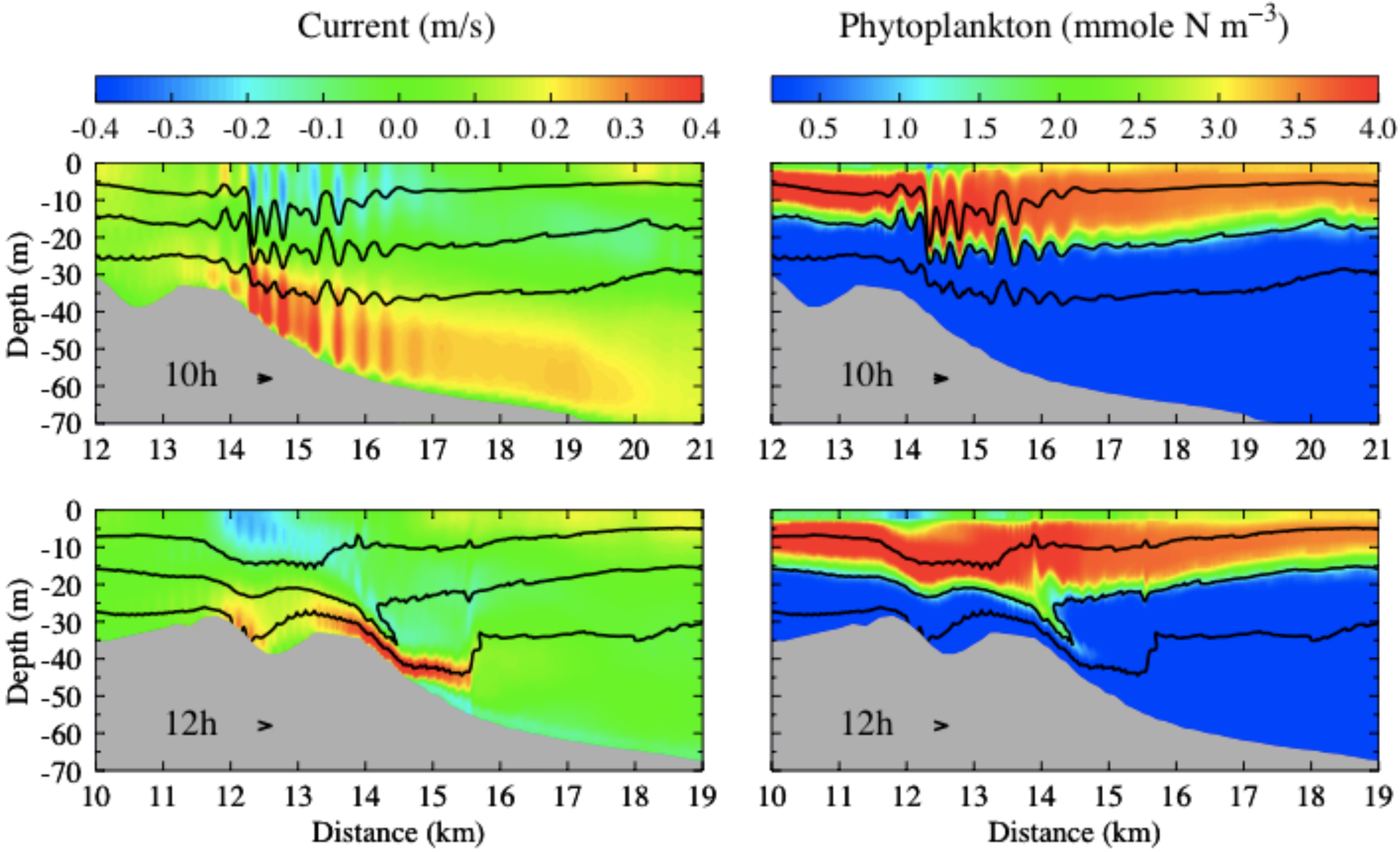
$$c_f \sim 1.16 c_o$$

Internal wave's impacts on plankton over Stellwagan Bank



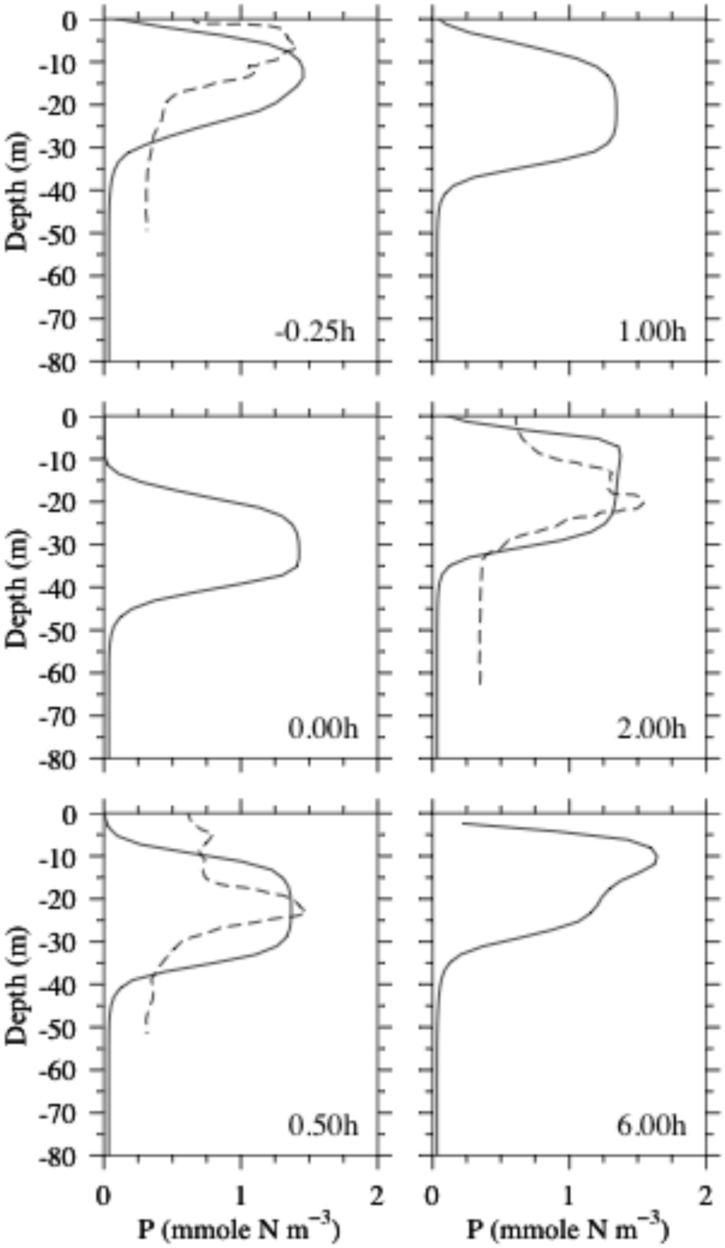


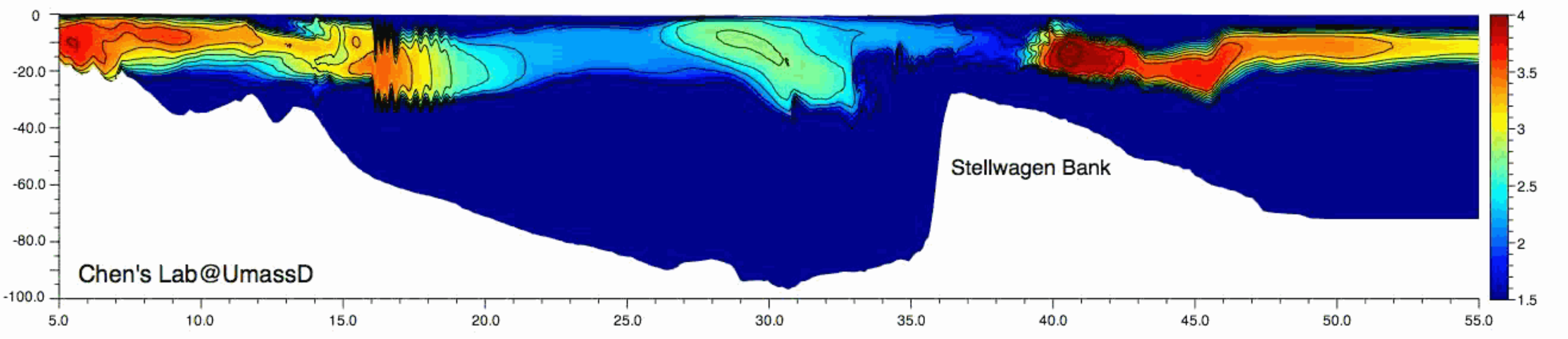

Phytoplankton (mmole N m^{-3})
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Depth (m)
0
-10
-20
-30
-40
-50
-1.00h
0.67h
0.00h
0.83h
0.17h
1.00h
0.33h
2.00h
0.50h
3.00h
Distance (km)
33
34
35
36
37
38
39
40
41
42
31
32
30
29


Current (m/s)
Phytoplankton (mmole N m^{-3})
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Depth (m)
0
-10
-20
-30
-40
-50
-60
-70
10h
12h
12
13
14
15
16
17
18
19
20
21
10
11
Distance (km)

Vertical migration of high phytoplankton concentration zone before, during and after the high-frequency internal waves pass.

Dashed line: Observation
Solid line: model




0
-20.0
-40.0
-60.0
-80.0
-100.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
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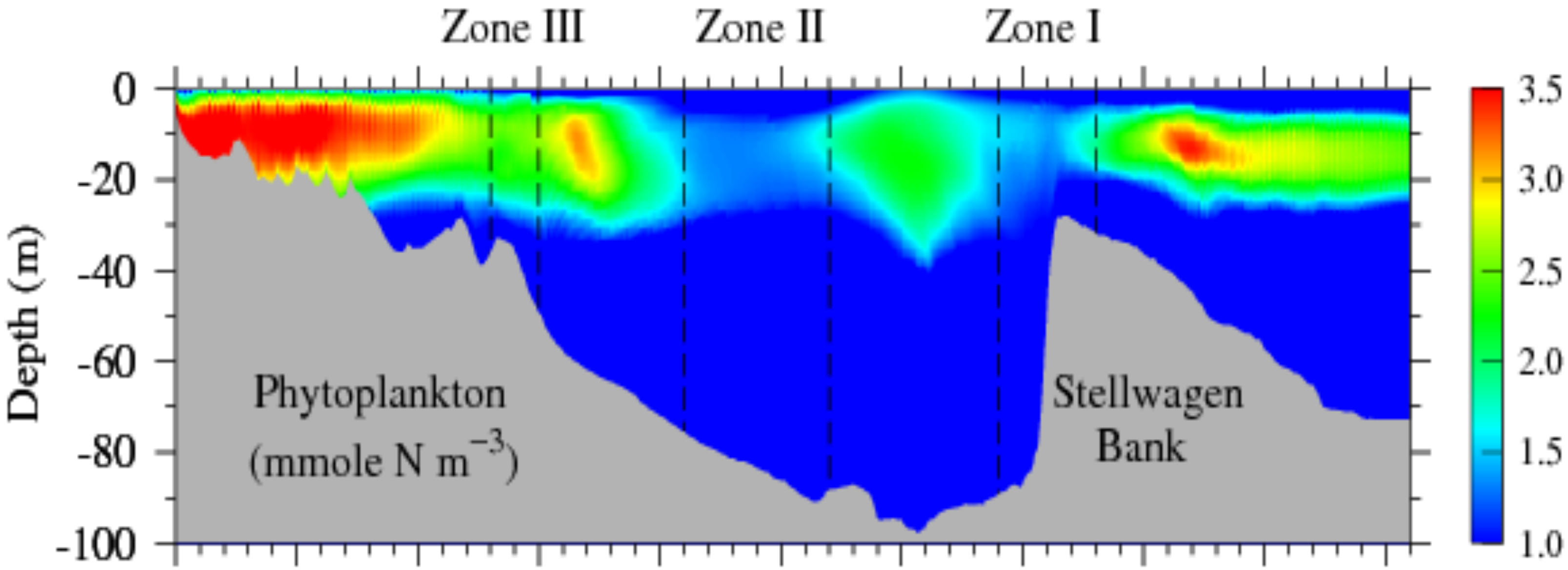
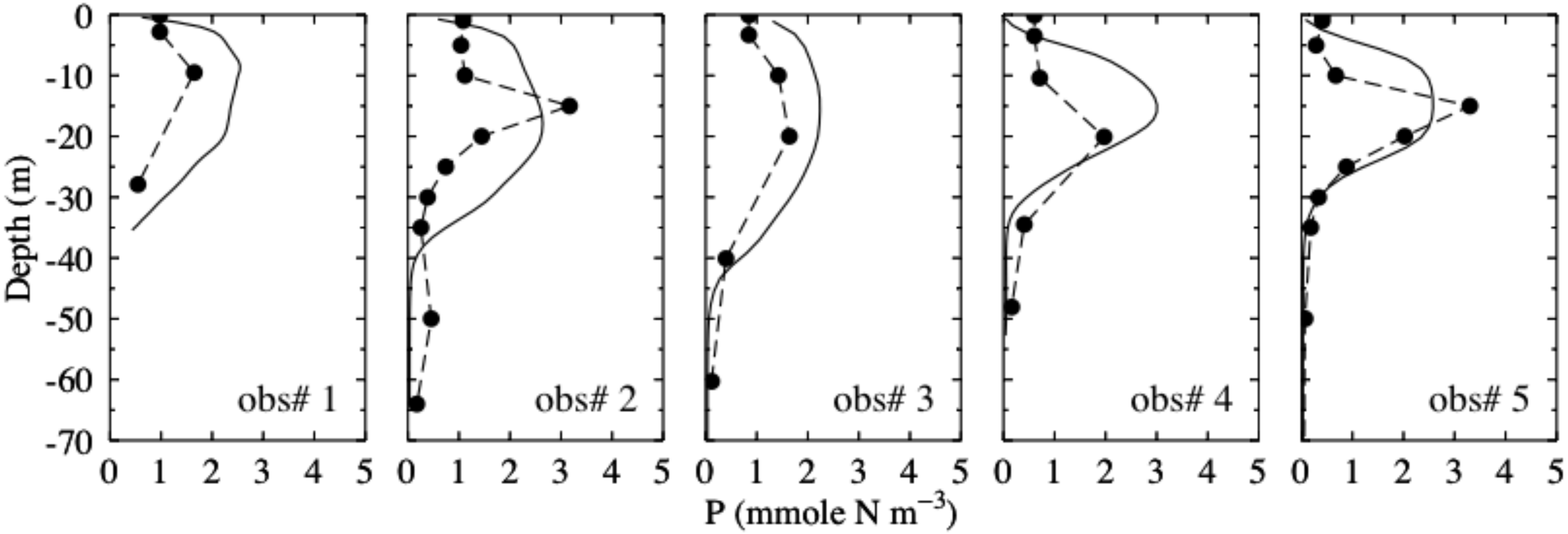
4
3.5
3
2.5
2
1.5

Tidally averaged distribution of phytoplankton concentraton

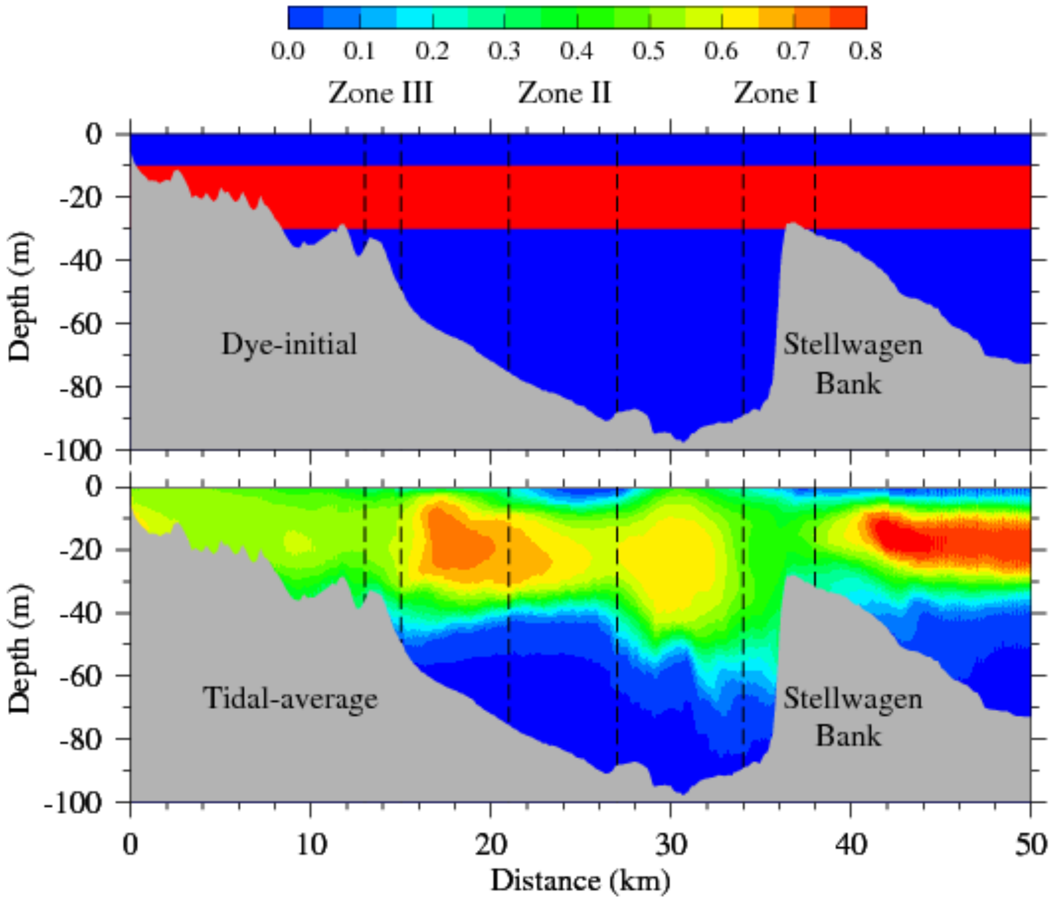


Model and data comparison



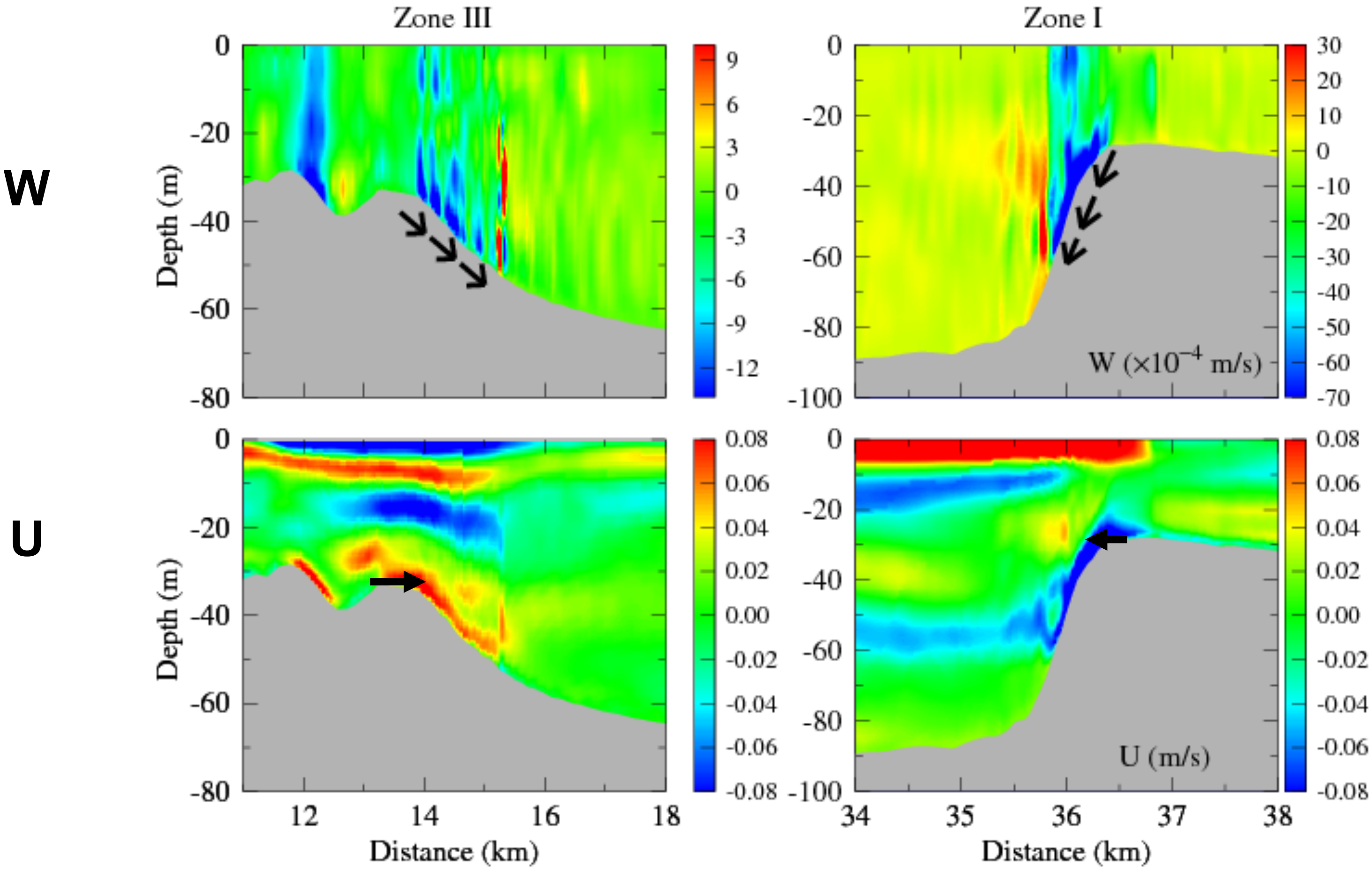
What process drives the patchy phytoplankton structure?

In dye release experiment (with no biology), resulting tidal-averaged dye concentration pattern similar to phytoplankton structure, suggesting *physical processes cause phytoplankton structure.*

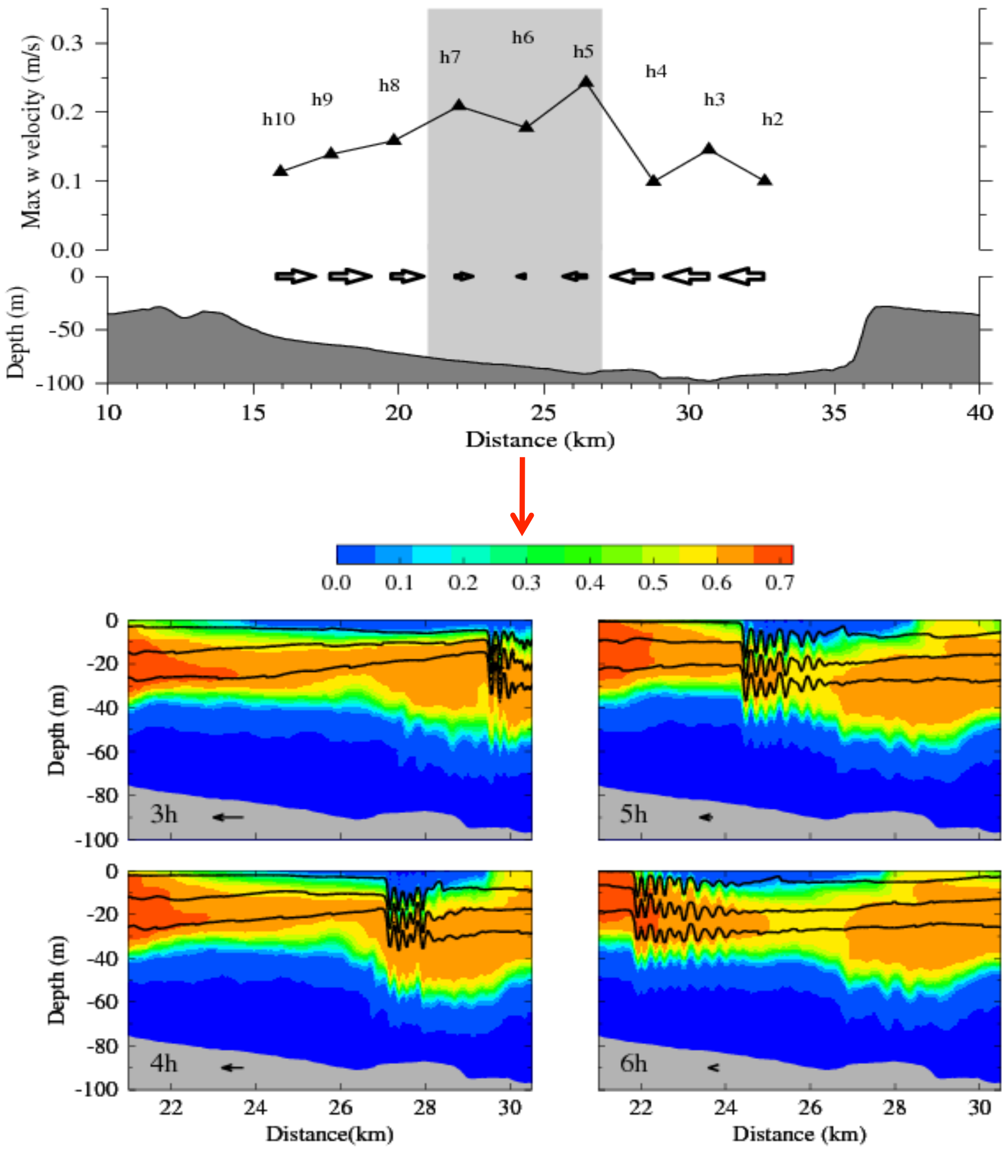


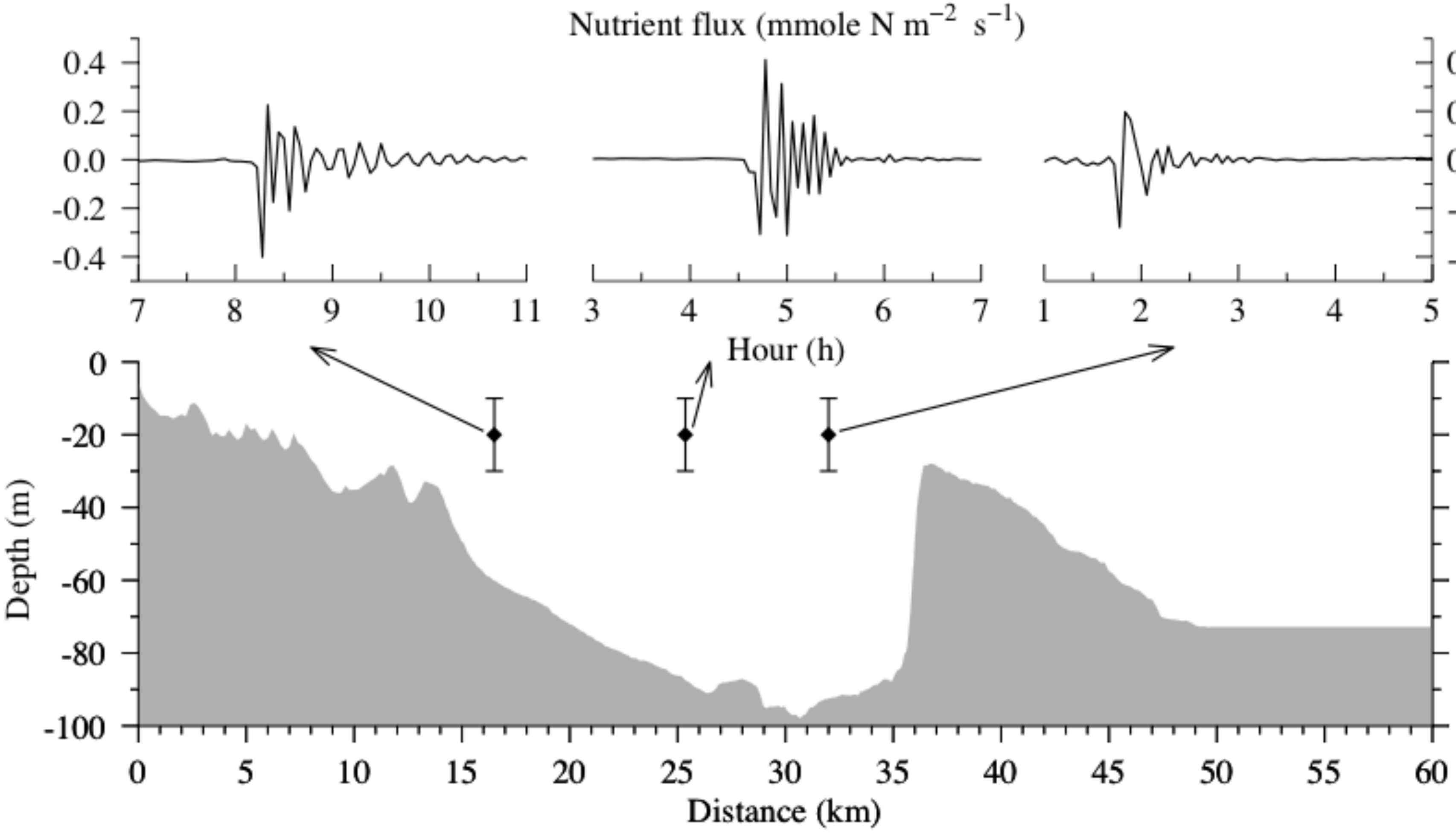
Zone III: Wave breaking causes increased dissipation and mixing process.

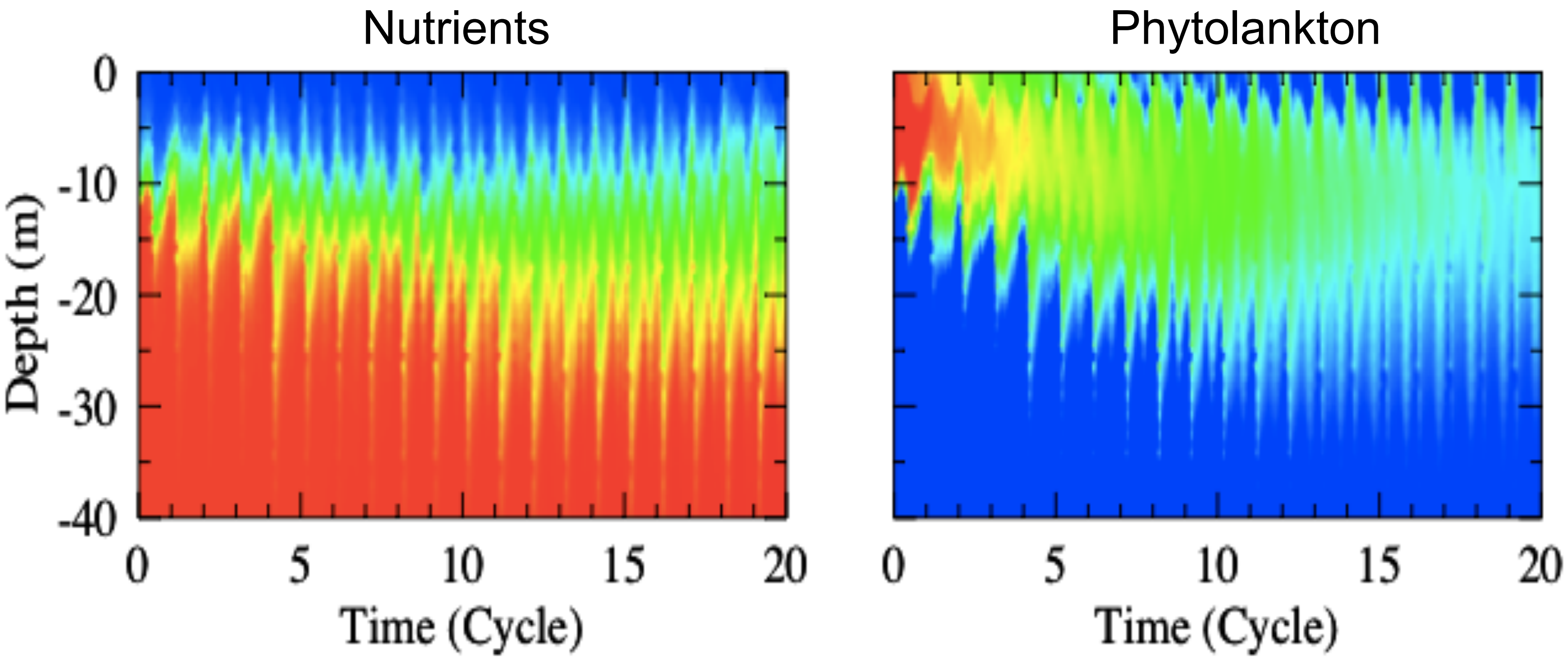
Zone I: low concentration caused by strong downwelling residual flow that advects phytoplankton into the deep region.



The nonlinear interaction of internal waves and tidal currents which significantly enhances the horizontal transport of phytoplankton that separate the phytoplankton patchiness at zone II.




Nutrient flux (mmole N m^{-2} s^{-1})
0.4
0.2
0.0
-0.2
-0.4
7
8
9
10
11
3
4
5
6
7
1
2
3
4
5
Hour (h)
Depth (m)
0
-20
-40
-60
-80
-100
0
5
10
15
20
25
30
35
40
45
50
55
60
Distance (km)



Nutrients

Phytolankton

Huary et al. (1979), Nature, 278, 22.

Don’t apply for Stellwagan Bank!

Summary

1. Internal waves over Stellwagan Bank is generated by a complex nonlinear process of tidal interaction over steep bottom topography under stratified condition. It follows Lee and Beardsley's (1974) mechanism.

2. The earth's rotation tends to transfer the cross-bank tidal kinematic energy to the along-bank direction, which results in weakening the intensity of sharp front at ebb-flood transition and thus lead to a faster propagation.

3. Complex plankton distribution observed over Stellwagan Bank is fully controlled by internal tidal plus high-frequency internal waves. Correcting the generation mechanism of internal waves has change our understanding of plankton dynamics in that region.

4. The mechanism discussed here should apply for other steep slope region where the tides is a key process to cause the internal waves.